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Electric propulsion for spacecraft

Research in the United States has brought two systems for creating beams of high-speed ions to a stage where they can be seriously considered for driving spacecraft on long inter-planetary journeys. Their use, however, must wait on the development of suitable nuclear power units

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PIONEERS of chemical rockets, including Goddard and Oberth, long ago recognised the possibility of using electrical energy to accelerate a propellant. Much greater propellant velocities (and hence much greater impulse per lb of propellant) could be obtained in this way, than by chemical means. No significant progress towards electric rockets was made, however, until the advent of nuclear fission made the necessary power-plant possible. Calculations by Shepard and Cleaver in Britain (1948, 1949) and Stuhlinger in the USA (1955, 1956) showed the substantial advantages in terms of payload, of electric-propulsion systems using fission power-plants. Although enough information was available for preliminary estimates of power-plant performance, however, it was clear that the electrical thrust-producing devices, or thrustors, would require a new technology.

The electric-propulsion research programme in the United States was therefore directed primarily at the development of thrustors. Work had already been started on nuclear power-plants for a variety of space applications, and it was hoped that some of these power-plants would be suitable for early trials of electric propulsion in space. It was expected that the problems in the realisation of these power-plants would be mostly developmental. As will be explained at the end of the article, the situation is now reversed: the thrustor programme is at present waiting on suitable power-plants.

Two main types.—Experimental work on a variety of thrustor concepts began in 1958 and 1959, but with special emphasis on one type, an electrostatic thrustor in which a vapour or gas was ionised by contact with a metal surface and accelerated by a steady electric field between two grids. There were several reasons for this emphasis on the "contact ionisation" concept. It gave promise of good overall efficiency; it lent itself to the division of the thrustor into distinct engineering components; and lastly (though not necessarily least) it was the first electric thrustor to be described in literature in anything like a workable design (by Stuhlinger in 1954).

The contact-ionisation thrustor is sketched in Figure 1. It makes use of the fact that an easily ionised atom (such as caesium) will lose an electron, and so acquire a positive charge, when it strikes a surface with a large affinity for electrons (such as tungsten). Caesium and tungsten have been used almost to the exclusion of other combinations. The ioniser must be hot enough to evaporate the ions in spite of electrical forces holding them, or the surface will quickly become coated with them and cease to function; the heat radiated from the hot ioniser, 1300° to 1500°K, represents the major loss of energy for this type of thrustor. The voltage difference between the ioniser and the accelerator electrode (typically, several thousand volts) gives the ions their high velocity of ejection at the rear of the thrustor.

Plainly, if only positive ions were ejected from the spacecraft, it would acquire a very large negative electric charge by the accumulation of excess electrons. To prevent that occurring, a "neutraliser" ejects electrons into the ion beam. The neutraliser has to be at a higher positive voltage than the accelerator, to prevent the electrons from going in the wrong direction and short-circuiting the ion accelerator.

The second major type of electrostatic thrustor uses bombardment by high-energy electrons to ionise the propellant. Conventional electron-bombardment sources (such as the von Ardenne "duoplasmatron") produced too dense a stream of ions to be transmitted by practical accelerator systems. The merit of the electron-bombardment thrustor, introduced by the author and Reader in 1960, lay in matching the ion source to the current-density requirements of a long-life electrostatic accelerator that gave a useful exhaust velocity.

The electron-bombardment thrustor (Figure 2) uses a hot cathode as the electron source. A field coil sets up a magnetic field which prevents them from moving directly towards the surrounding anode, which they can reach only by collision with atoms of propellant vapour in the ionisation chamber. Some of the lisions ionise propellant atoms, which then diffuse to the accelerator system, where the voltage between the two grids (again several thousand volts) sweeps them out at high velocity. Electrons are again added to the ion beam by the neutraliser.

Both mercury and caesium have been used as propellants in the electron-bombardment thrustor. The major losses of energy arise in heating the cathode, in sustaining the electron current in the ionisation chamber (of the order of 500 eV per ion), and in the power to the magnetic-field winding. (This last loss is eliminated by using a light-weight permanent magnet introduced by Reader in 1963.) The neutral propellant atoms that escape without being ionised (5 to 20 per cent) also constitute a significant loss for this type of thrustor.

Technology of contact-ionisers.—Contact-ioniser work has centred on the porous-tungsten type, through which the caesium vapour diffuses to emerge as ions on the far side. It appears to offer the best combination of high ion currents and low rates of escape of neutral atoms. The ioniser usually consists of a number of pieces of porous tungsten, in the shape of

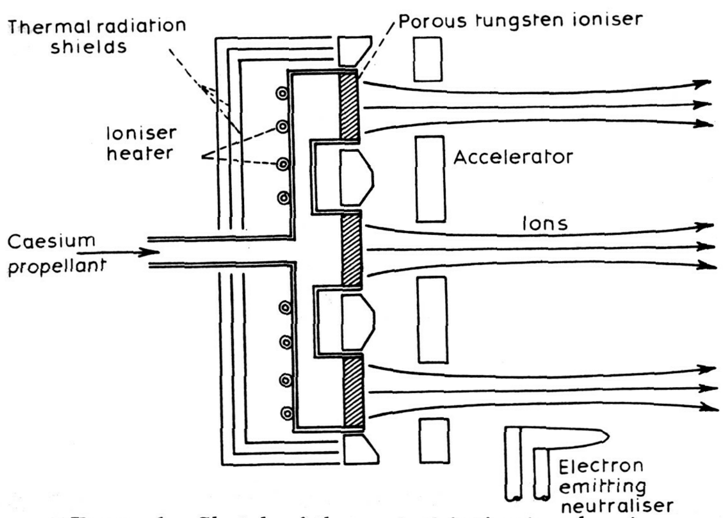

FIGURE 1. *Sketch of the contact-ionisation thrustor.*

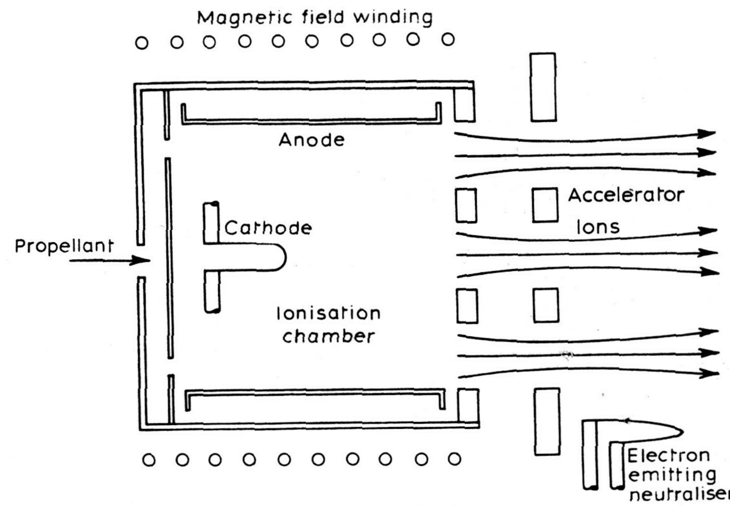

FIGURE 2. *Sketch of the electron-bombardment thrustor.*

either strips (Figure 3) or buttons (Figure 4 overleaf). The discussions about which shape is best have become reminiscent of arguments for and against various cylinder arrangements in automobile engines.

The progress of contact-ionisation thrustors is closely linked to the technology of porous tungsten, the machining of which was one of the early problems. Nowadays it is usual to fill the porous tungsten with copper, machine it by normal methods and then remove the copper; this sequence permits precise machining without the usual loss of porosity.

Analyses of the caesium diffusion and ionisation processes indicate that a very fine pore structure is desired. But the fine powders that give it its structure undergo further sintering (with accompanying dimensional changes) during normal use. Spherical powder grains (as reported by Kuskevics and Thompson in 1963) give the best available combination of fine pore structure and low sintering rates.

Technology of electron-bombardment thrustors.—The major problem of the electron-bombardment thrustor (Figure 5) has been erosion of the cathode by ion-bombardment. Cathodes in which a large quantity of the active oxide-emitter is held in a metal matrix have been operated as long as 3000 hours in component tests and over 600 hours in a complete thrustor. Considerable improvement is necessary, however, before the goal of 10 000 hours can be reached—which is roughly the shortest lifetime required for interplanetary missions.

An electron-bombardment cathode that appears certain of reaching a 10 000 hour lifetime is the "auto-cathode" developed by Speiser. Previously, mercury vapour was used almost exclusively as the propellant for electron-bombardment thrustors. In an interesting mating of contact-ionisation and electron-bombardment technology, Speiser used the usual contact-thrustor propellant (caesium) in an electron-bombardment thrustor of his own design. Here, the caesium propellant is passed through the cathode and sufficient is deposited to replenish the emitter coating. Moreover, the bombardment by ions is turned to advantage by using it to supply the necessary cathode heating.

Neutralisers.—The need for some form of neutralisation was recognised in the earliest proposals for electrostatic thrustors. The subsequent development of neutralisers is one of the more interesting facets of electric propulsion. The basic requirements are (1) equal *rates* for the ejection of positive and negative charges (current neutralisation) to avoid building up a large charge on the space vehicle, and (2) equal *densities* of positive and negative charges in the beam (charge neutralisation) to avoid marked effects of electrical repulsion between charges of the same sign within the beam.

The earliest concept of neutralisation supposed that, since oppositely charged particles attract each other, all one had to do was to provide for the emission of electrons somewhere near the ion beam. Electrostatic attraction would then assure that the proper number of electrons were pulled into the beam and evenly distributed. The next step was to obtain mathematical descriptions of this process. Collisions between electrons and ions were assumed to be unimportant—partly because it looked as if they would be infrequent but mainly because the mathematics appeared to be impossible without this assumption.

The solutions obtained indicated that the electrons had to be introduced at not more than twice the ion velocity if a neutralised beam was to be obtained far from the vehicle. Unfortunately, the velocity with which electrons are emitted from a hot surface, without any acceleration, would exceed twice the ion velocity for many combinations of design and operating conditions. And, at low electron velocities, repulsion between the electrons would retard their emission, so that the electron source would have to be hundreds of times larger in area than the ion source!

According to these analytical studies, then, neutralisation appeared very difficult. Yet by 1960 a number of ion thrustors were operating with steady beam currents of over 100 milliamp in conditions that should have caused neutralisation problems, and none were encountered; there was no evidence of "blow-up" or "turn-around" of the ion beam. The theoretical analysis was clearly inadequate.

Then Sellen and Shelton showed that secondary electrons produced by the action of the beam on the surrounds of the experimental test facility would cause charge neutralisation even if no neutraliser were used. So Sellen and Kemp used a pulsed beam and made

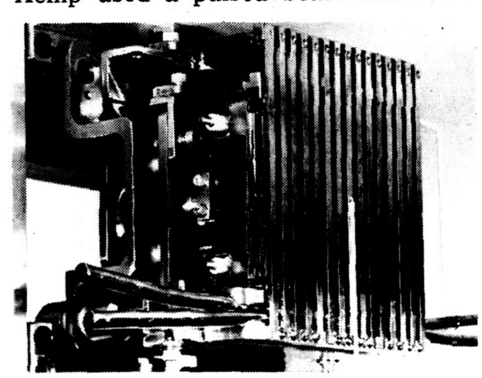

FIGURE 3. *Contact-ionisation thrustor under development by Hughes Research Laboratories.*

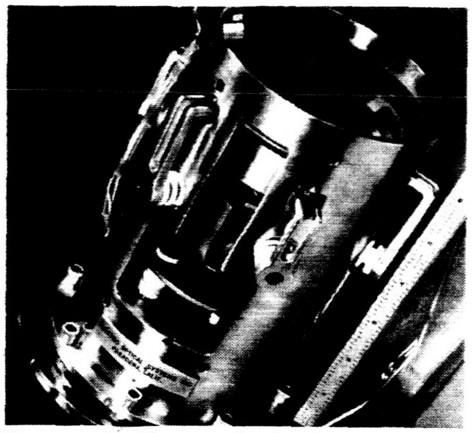

FIGURE 4. *Contact-ionisation thrustor designed at Electro-Optical Systems.*

measurements during the time that the beam was travelling from the thrustor to the other end of the test facility, and before any significant number of secondary electrons could be emitted. In this way, at least over the length of the beam, they obtained a close simulation of space, and eventually extended the length of the pulsed beam to about 80 feet in a NASA vacuum test facility. Although space tests will be required for final verification, there now appears to be little doubt that neutralisation will be obtained without difficulty.

The failure of the analytical studies was due, as is now known, to the basic assumption of no collisional effects. Even infrequent collisions will eventually reduce the electrons to acceptable random motion, and when the electrons are, at the outset, much faster than the ions, "collective" collision processes can be far more effective than two-body collisions.

Prospects.—Electrostatic thrustor efficiencies of 60 to 80 per cent are presently possible, at exhaust velocities from 40 to 100 kilometres per second (which covers much of the range of interest). Although the electron-bombardment thrustor apparently has a slight edge in efficiency, there is no guarantee that it will retain it in the future. Regardless of which type of thrustor ultimately predominates, the presently achievable efficiencies are adequate for most proposed missions.

The emphasis in electrostatic thrustor research has therefore shifted towards achieving long lifetimes. The porous ioniser and cathode problems have already been mentioned, but there is another lifetime problem that both thrustors have in common: "charge-exchange" erosion of the accelerator system. Virtually all the ions produced on the contact-ioniser or in the ionisation chamber can be focused to miss the accelerator electrodes, but, in traversing the accelerator system, some ions collide with escaping neutral atoms and ionise them. The slow ions so produced within the accelerator structure are likely to strike the accelerator electrodes and erode them. This effect can be reduced by reducing the ion-beam current densities—or with large enough thrustor exit areas. For the electron-bombardment thrustor a large ion-beam area means a heavy, but tolerable, thrustor weight. For the contact-ionisation thrustor, with a smaller escape of neutral atoms, the increase in weight to avoid accelerator erosion is not as serious. But the energy losses from the hot contact-ioniser are greater when the area is increased. However, the reduction in efficiency is tolerable. The research programme on ion thrustors has brought us to where reasonable efficiencies and lifetimes are in sight, even if more advanced thrustor concepts should not prove successful.

Improved systems.—As for improved electrostatic thrustors, the most promising concept is the use of heavier charged particles. The energy required to charge a particle constitutes a loss. This loss can be made smaller, relative to the kinetic energy acquired by the particle in being accelerated to a given exhaust velocity, by making the particle heavier. A larger accelerating voltage is then required. Interest thus ranges over particles from the heavier elements, through heavy molecules, to colloidal particles with several thousand atomic-mass units per electronic charge. Heavy molecules have been investigated, but excessive fragmentation has accompanied the ionisation process. Colloidal particles appear promising, but a good evaluation cannot yet be made. As for electric thrustors of types other than electrostatic—for example, electromagnetic plasma accelerators—it is always possible that new concepts will prove worthwhile, but electrostatic thrustors currently have the best performance for interplanetary missions (see Figure 6).

Power sources.—The importance of nuclear power sources to electric propulsion makes it appropriate to say a few words about them. Evvard (1963) has pointed out the comparative lack of progress in power generation. To be useful for interplanetary missions using electric propulsion, the power supply should have a lifetime of about 10 000 hours and a weight of not more than about 10 kilogrammes per kilowatt. No power-generation system is as yet far enough along in development to be reasonably sure of meeting these requirements.

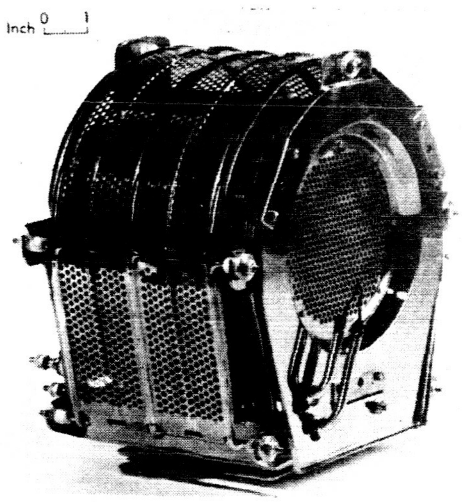

FIGURE 5. *Electron-bombardment thrustor designed at the Lewis Research Center for mercury propellant.*

It is now apparent that a thrustor is an easier device to build than a power source. The only natural limit found for the performance of electrostatic thrustors was charge-exchange impingement. For the nuclear turbo-electric systems that appear nearest realisation there are the limits of nuclear radiation from the reactor, thermodynamic efficiency for the conversion of heat to electricity, the radiation law for rejecting heat from the radiators, and the impingement of meteorites on these radiators. The many studies of such power sources have shown that these natural limits can best be dealt with (and still meet the requirements for electric propulsion) by making very large power supplies. While there is little doubt that satisfactory power sources can be built, the sizes needed make the development process a slow one.

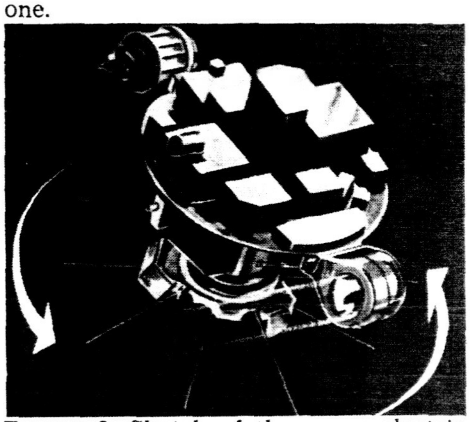

FIGURE 6. *Sketch of the space electric rocket test (SERT) experiment, successfully performed by NASA earlier this month, in which two (different) thrustors demonstrated their ability to produce thrust by rotating the space vehicle.*